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## PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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<input checked="" type="checkbox"/> Additional inventors are being named on the _____ separately numbered sheets attached hereto					
TITLE OF THE INVENTION (280 characters max)					
SHAPE MEMORY POLYMER COATED ELECTRODES					
Direct all correspondence to: CORRESPONDENCE ADDRESS					
<input type="checkbox"/> Customer Number		<input type="text"/>		<div>Place Customer Number Bar Code Label here</div>	
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ENCLOSED APPLICATION PARTS (check all that apply)					
<input checked="" type="checkbox"/> Specification		Number of Pages		<input type="checkbox"/> CD(s), Number	
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METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT (check one)					
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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.					
<input type="checkbox"/> No.					
<input checked="" type="checkbox"/> Yes, the name of the U.S. Government agency and the Government contract number are: NIH Grant No. DC00566					

Respectfully submitted,

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Date

12-3-03

REGISTRATION NO.

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(if appropriate)

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PROVISIONAL PATENT APPLICATION

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**SHAPE MEMORY POLYMER COATED ELECTRODES**

**GRANT INFORMATION**

10

Research in this application was supported in part by a grant from the National Institute of Health (NIH Grant No. DC00566). The Government has certain rights in the invention.

**BACKGROUND OF THE INVENTION**

15

**1. FIELD OF THE INVENTION**

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Generally, the present invention relates to coated electrodes. More specifically, the present invention relates to electrodes capable of insertion into the brain.

**2. DESCRIPTION OF RELATED ART**

25

Systems for electrically monitoring and stimulating the brain are increasingly important in the medical diagnosis and treatment of various brain disorders, such as epilepsy, Parkinson's disease, sleep disorders, migraine, and psychiatric ailments. Therapeutic neurostimulatory devices can include one or more leads having at least one electrode operatively situated in the brain or other neural tissue and linked to a signal processor for detecting neurological activity and to a pulse generator for providing electrical stimuli.

30

For several years research has been conducted in attempts to establish communication through living neurons, to communicate to the human brain information, which can no longer be provided by a person's own eyes or ears, to stimulate paralyzed muscles, to stimulate autonomic nerves, as to control bladder  
5 function or pace the heart, or to control prosthetic limbs.

It is well known that electrical stimulation of certain nerves and certain regions of the brain can be perceived consciously, and research is being performed with the intention of eventually learning how to stimulate nerves in ways that can  
10 provide useful information to a person whose ability to hear or to see has been lost.

To utilize neural prostheses, electrical connections must be made to living neurons. Such connections must be made by extremely small electrodes in order to isolate currents within small regions of living tissue. Active electrode sites can be  
15 placed very close to nerve cells, and electrical activity at the active electrode sites can be used to provide stimulation to the nerves. To limit the mechanical trauma caused by insertion and chronic presence of electrode structures, the entire electrode structure and associated wires must be as small as possible consistent with the required ability to conduct electrical energy, and must be of materials which  
20 will not react with the living body.

Implanted electrodes and conductors connected to them must be electrically insulated very effectively, because of the very small voltages and currents being utilized. The localized nature of the electrical potential gradient that must be  
25 detected by a microelectrode, and the fragility of neurons, dictate a microelectrode tip with small dimensions (typically less than 5 x 25 microns), which in turn produces high impedance in the interface of metal to electrolyte. Since the probe as a whole must have a slender profile to minimize disruption of tissue, the requirement to minimize shunt losses along the insulated shank of the probe falls  
30 on a very thin dielectric coating which must be cleanly excluded from the tiny exposed tip or window. Insulating coatings on conductors must be free from

pinholes and should be tightly adhered to the insulated wires and parts of electrodes. It is known that there are some biologically compatible dielectric materials that can be applied consistently and successfully as coatings of uniform thickness for such small structures as are found in microelectrodes to be used for neural prostheses. An insulating coating of Parylene-C™, a polymerized diparachloroxylyene produced by the Union Carbide Corporation, is known to have the required biological compatibility and electrical insulation qualities and can be applied successfully to electrode surfaces, but the techniques previously available for removing portions of such a coating have not been entirely satisfactory.

An additional problem associated with the prior art electrodes is that the act of inserting the electrode into the brain causes damage to the brain tissue. Specifically, the insertion of the electrode causes tissue inflammation and necrotic cell death. More importantly, a long-term reactive astrocytic reaction ensues that results in physical blockage of the electrode by a surrounding sheath of reactive astrocytes. The sheath of reactive astrocytes prevents the electrode from receiving signals from the surrounding neurons.

In an attempt to prevent the formation of the sheath of reactive astrocytes, individuals have attempted to quickly insert the electrodes into the brain tissue. The method of insertion has not been effective at eliminating the problem associated with the astrocyte sheath. It would therefore be beneficial to develop an electrode that, upon insertion into brain tissue does not cause formation of the sheath of reactive astrocytes.

## SUMMARY OF THE INVENTION

According to the present invention, there is provided an implantable electrode having a shape-memory polymer coated electrode. A coating for an electrode, the coating includes a shape-memory polymer. A method for inserting

an electrode into brain tissue by inserting an implantable electrode having a shape-memory polymer coated electrode into brain tissue.

5

## DESCRIPTION OF THE DRAWINGS

Other advantages of the present invention are readily appreciated as the same becomes better understood by reference to the following detailed description  
10 when considered in connection with the accompanying drawings wherein:

Figure 1 is a schematic of the shape memory effect in polymers as defined by four critical temperatures;

15 Figures 2A and B are photographs of sections of olfactory bulb with (Figure 2A) 25  $\mu\text{m}$  gold microwire or (Figure 2B) embedded smp/gold electrode (150 X 300  $\mu\text{m}$ ); scale bar 300  $\mu\text{m}$ , arrows point to gold microwire;

Figures 3A and B are photographs showing tissue response to implantation  
20 of 100 X 200  $\mu\text{m}$  smp one week post-implantation; the scale bar is 200  $\mu\text{m}$ ;

Figures 4A and B are photographs showing tissue response to implantation of 100 X 200  $\mu\text{m}$  smp after two weeks; the scale bar is 200  $\mu\text{m}$ ;

25 Figures 5A and B are photographs showing tissue response to a one week "slowly" (1 mm/ 40 minutes) inserted smp/gold wire implant (75 X 200  $\mu\text{m}$ );

Figures 6A and B show force measurement; Figure 6A shows a digital micrograph of an smp beam partially inserted into the olfactory bulb; and Figure 6B  
30 is a force-displacement graph;

Figures 7A-D are photographs showing two different designs (Figures 7A and B, and Figures 7C and D) for smp linear actuators with 25  $\mu$ m embedded gold wire in the compressed state ((Figure 7A) and (Figure 7C)) and following thermal actuation ((Figure 7B) and (Figure 7D)); bars are 1 mm; and

5

Figures 8A and B are photographs showing the shape memory effect in polyglycolic acid (PGA); Figure 8A shows the shape after deformation at 120°C and Figure 8B shows the subsequent recovery above  $T_g$ ; the bar is 1 mm.

10

## DETAILED DESCRIPTION OF THE INVENTION

Generally, the present invention provides shape memory polymers (smp) with embedded single or multiple microwire or nanowire conductors. The shape memory polymers can be used as electrodes that can be used for long-term recording and stimulation in different tissues in the body including brain tissue. The smp electrodes are capable of deployment at slow rates (minutes to days) post-implantation thereby minimizing adverse tissue reactivity. Smp electrodes operate on the principle of using low modulus materials to better match the mechanical properties of tissue.

20

Slow deployment (hours to days) of electrodes through thermal actuation of shape memory polymers (smp's) greatly diminishes the inflammatory astrocytic scar reaction that adversely affects long-term electrode performance. In addition, because design of biocompatible electrodes places specific constraints on electrical properties parallel design of low power implant electronics were incorporated. The biological micro-probes use a combination of MEMS based fabrication technology (Micro Electrical Mechanical Systems) and cell biological approaches; a process termed CEMS, or Cellular Engineering Micro Systems. Utilizing sensors and actuators based in MEMS technology with microelectronics for control, signal processing and telemetry, the fabrication of devices allows micro scale movement of neuronal probes *in vivo*. CEMS implants provide significant advantages over

25

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existing probes through long-term interaction with neurons in a "wire free" environment.

5 A polymer is a shape memory polymer if the original shape of the polymer is recovered by heating it above a shape recovering temperature (defined as the  $T_{trans}$  of a soft segment) even if the original molded shape of the polymer is destroyed mechanically at a lower temperature than the shape recovering temperature, or if the memorized shape is recoverable by application of another stimulus.

10 As used herein, the term "segment" refers to a block or sequence of polymer forming part of the shape memory polymer.

As used herein, the terms hard segment and soft segment are relative terms, relating to the  $T_{trans}$  of the segments. The hard segment(s) has a higher  $T_{trans}$  than  
15 the soft segment(s). The ratio by weight of the hard segment:soft segments is between about 5:95 and 95:5, preferably between 20:80 and 80:20.

As used herein, the term "biodegradable" refers to materials that are bioresorbable and/or degrade and/or break down by mechanical degradation upon  
20 interaction with a physiological environment into components that are metabolizable or excretable, over a period of time from minutes to three years, preferably less than one year, while maintaining the requisite structural integrity. As used herein in reference to polymers, the term "degrade" refers to cleavage of the polymer chain, such that the molecular weight stays approximately constant at the oligomer level  
25 and particles of polymer remain following degradation. The term "completely degrade" refers to cleavage of the polymer at the molecular level such that there is essentially complete mass loss. The term "degrade" as used herein includes "completely degrade" unless otherwise indicated.

30 Shape memory polymers can be thermoplastic, thermoset, interpenetrating networks, semi-interpenetrating networks, or mixed networks. Polymers can be a

single polymer or a blend of polymers. Polymers can be linear, branched, thermoplastic elastomers with side chains or any kind of dendritic structural elements. Stimuli causing shape change can be temperature, ionic change, pH, light, electric field, magnetic field or ultrasound.

5

Thermoplastic shape memory materials can be shaped (e.g. molded) to a desired shape above the  $T_{\text{trans}}$  of the hard segment(s) and cooled to a temperature below the shape recovering temperature, where the polymer can undergo mechanical deformation, and strains are generated in the polymer. The original  
10 shape of the deformed polymers can be recovered by heating them to a temperature higher than their shape recovering temperature. Above this temperature, the strains in the polymer are relieved, allowing the polymer to return to its original shape. In contrast, thermoset shape memory materials are shaped to a desired shape before the macromonomers used to form the thermoset polymers  
15 are polymerized. After the shape has been fixed, the macromonomers then are polymerized.

The polymer compositions are preferably compressible by at least one percent or expandable by at least five percent of the original thickness at a  
20 temperature below the shape recovering temperature, with the deformation being fixed by application of a stimulus such as heat, light, ultrasound, magnetic fields or electric fields.

When significant stress is applied, resulting in an enforced mechanical  
25 deformation at a temperature lower than the shape recovering temperature, strains are retained in the soft segments, or amorphous regions, and bulky shape change is kept even after the partial liberation of strain by the elasticity of the polymer. If the configuration of the molecular chains is disturbed by influencing the regulated arrangement of molecular chains at a temperature lower than the glass transition  
30 temperature, rearrangement of the molecular chains is assumed to occur through the increase of the volume size and the decrease of the free volume content. The

original shape is recovered by the contraction of the hard segment aggregates by the elevation of the temperature according to rigid control of chain conformations and the shape of the polymer is restored to the memorized shape.

5           In addition to changes in state from a solid to liquid state (melting point or glass transition temperature), hard or soft segments can undergo ionic interactions involving polyelectrolyte segments or supramolecular effects based on highly organized hydrogen bonds. The SMP can undergo solid state to solid-state transitions (e.g. a change in morphology). Solid state to solid state transitions are  
10 well known to those of skill in the art, for example as in poly(styrene-block-butadiene).

          An object formed using shape memory polymers can be prepared to control the direction of change during recovery. In other words, contraction and/or  
15 expansion can occur along one or more dimensional axes depending how the polymers are shaped and stressed. For example, in a SMP fiber, the change in shape can be limited to one dimension, such as along the length.

          In another embodiment, the thermal and electrical conductivity of the SMP  
20 materials can be changed in response to changes in temperature.

          The moisture permeability of the compositions can be varied, especially when the polymer is formed into a thin film (i.e., less than about 10  $\mu\text{m}$ ). Some polymer compositions, in their original shape, have a sufficient permeability such  
25 that molecules of water vapor can be transmitted through the polymer film, while water molecules are not large enough to penetrate the polymer film. The resulting materials have low moisture permeability at temperatures below room temperature and high moisture permeability at temperatures above room temperature.

30           The polymers incorporate "hard" and "soft" segments. The segments preferably are oligomers. As used herein, the term "oligomer" refers to a linear

chain molecule having a molecular weight up to 15,000 Daltons. The polymers forming the segments are selected based on the desired glass transition temperature(s) (if at least one segment is amorphous) or the melting point(s) (if at least one segment is crystalline), which in turn is based on the desired applications, taking into consideration the environment of use. Preferably, the number average molecular weight of the polymer segment is greater than 400, and is preferably in the range of between 500 and 15,000.

10 The transition temperature at which the polymer abruptly becomes soft and deforms, can be controlled by changing the monomer composition and the kind of monomer, which enables one to adjust the shape memory effect at a desired temperature. The thermal properties of the polymers can be detected, for example, by dynamic mechanical thermoanalysis or differential scanning calorimetry (DSC) studies. In addition the melting point can be determined using a standard melting point apparatus.

20 The polymers can be thermoset or thermoplastic polymers, although thermoplastic polymers are preferred due to their ease of molding. Thermosets, however, are preferred in some applications, since they generally are softer than physically crosslinked polymer in their original shape at temperatures greater than  $T_{trans}$ .

25 Preferably, the degree of crystallinity of the polymer or polymeric block(s) is between 3 and 80%, more preferably between 3 and 60%. When the degree of crystallinity is greater than 80% while all soft segments are amorphous, the resulting polymer composition has poor shape memory characteristics.

30 The tensile modulus of the polymers below the  $T_{trans}$  is typically between 50 MPa and 2 GPa (gigapascals), whereas the tensile modulus of the polymers above the  $T_{trans}$  is typically between 1 and 500 MPa. Preferably, the ratio of elastic

modulus above and below the  $T_{\text{trans}}$  is 20 or more. The higher the ratio, the better the shape memory of the resulting polymer composition.

5 The polymer segments can be natural or synthetic, although synthetic polymers are preferred. The polymer segments are biodegradable. In general, these materials degrade by hydrolysis, by exposure to water or enzymes under physiological conditions, by surface erosion, by bulk erosion, or a combination thereof. Non-biodegradable polymers preferably do not include aromatic groups, other than those present in naturally occurring amino acids.

10 The polymers are selected based on the desired glass transition temperature(s) (if at least one segment is amorphous) or the melting point(s) (if at least one segment is crystalline), which in turn is based on the desired applications, taking into consideration the environment of use. Preferably, the number average molecular weight of the polymer block is greater than 400, and is preferably in the range of between 500 and 15,000.

15 The polymer can be in the form of a hydrogel (typically absorbing up to about 90% by weight of water), and can optionally be ionically crosslinked with multivalent ions or polymers. Ionic crosslinking between soft segments can be used to hold a structure, which, when deformed, can be reformed by breaking the ionic crosslinks between the soft segments. The polymer can also be in the form of a gel in solvents other than water or aqueous solutions. In these polymers, the temporary shape can be fixed by hydrophilic interactions between soft segments.

20 Representative natural polymer blocks or polymers include proteins such as zein, modified zein, casein, gelatin, gluten, serum albumin, and collagen, and polysaccharides such as alginate, celluloses, dextrans, pullulane, and polyhyaluronic acid, as well as chitin, poly(3-hydroxyalkanoate)s, especially poly( $\beta$ -hydroxybutyrate), poly(3-hydroxyoctanoate) and poly(3-hydroxyfatty acids).

Representative natural biodegradable polymer blocks or polymers include polysaccharides such as alginate, dextran, cellulose, collagen, and chemical derivatives thereof (substitutions, additions of chemical groups, for example, alkyl, alkylene, hydroxylations, oxidations, and other modifications routinely made by those skilled in the art), and proteins such as albumin, zein and copolymers and blends thereof, alone or in combination with synthetic polymers.

Representative synthetic polymer blocks or polymers include polyphosphazenes, poly(vinyl alcohols), polyamides, polyester amides, poly(amino acid)s, synthetic poly(amino acids), polyanhydrides, polycarbonates, polyacrylates, polyalkylenes, polyacrylamides, polyalkylene glycols, polyalkylene oxides, polyalkylene terephthalates, polyortho esters, polyvinyl ethers, polyvinyl esters, polyvinyl halides, polyvinylpyrrolidone, polyesters, polylactides, polyglycolides, polysiloxanes, polyurethanes and copolymers thereof. Examples of suitable polyacrylates include poly(methyl methacrylate), poly(ethyl methacrylate), poly(butyl methacrylate), poly(isobutyl methacrylate), poly(hexyl methacrylate), poly(isodecyl methacrylate), poly(lauryl methacrylate), poly(phenyl methacrylate), poly(methyl acrylate), poly(isopropyl acrylate), poly(isobutyl acrylate) and poly(octadecyl acrylate).

20

Synthetically modified natural polymers include cellulose derivatives such as alkyl celluloses, hydroxyalkyl celluloses, cellulose ethers, cellulose esters, nitrocelluloses, and chitosan. Examples of suitable cellulose derivatives include methyl cellulose, ethyl cellulose, hydroxypropyl cellulose, hydroxypropyl methyl cellulose, hydroxybutyl methyl cellulose, cellulose acetate, cellulose propionate, cellulose acetate butyrate, cellulose acetate phthalate, carboxymethyl cellulose, cellulose triacetate and cellulose sulfate sodium salt. These are collectively referred to herein as "celluloses".

25

Representative synthetic degradable polymer segments include polyhydroxy acids, such as polylactides, polyglycolides and copolymers thereof; poly(ethylene

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terephthalate); polyanhydrides, poly(hydroxybutyric acid); poly(hydroxyvaleric acid); poly[lactide-co-(s-caprolactone)]; poly[glycolide-co-(s-caprolactone)]; polycarbonates, poly(pseudo amino acids); poly(amino acids); poly(hydroxyalkanoate)s; polyanhydrides; polyortho esters; and blends and copolymers thereof. Polymers containing labile bonds, such as polyanhydrides and polyesters, are well known for their hydrolytic reactivity. Their hydrolytic degradation rates can generally be altered by simple changes in the polymer backbone and their sequence structure.

10        Examples of non-biodegradable synthetic polymer segments include ethylene vinyl acetate, poly(meth)acrylic acid, polyamides, polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyvinylphenol, and copolymers and mixtures thereof.

15        Hydrogels can be formed from polyethylene glycol, polyethylene oxide, polyvinyl alcohol, polyvinyl pyrrolidone, polyacrylates, poly(ethylene terephthalate), poly(vinyl acetate), and copolymers and blends thereof. Several polymeric blocks, for example, acrylic acid, are elastomeric only when the polymer is hydrated and hydrogels are formed. Other polymeric blocks, for example, methacrylic acid, are crystalline and capable of melting even when the polymers are not hydrated. Either  
20        type of polymeric block can be used, depending on the desired application and conditions of use. For example, shape memory is observed for acrylic acid copolymers only in the hydrogel state, because the acrylic acid units are substantially hydrated and behave like a soft elastomer with a very low glass transition temperature. The dry polymers are not shape memory polymers. When  
25        dry, the acrylic acid units behave as a hard plastic even above the glass transition temperature and show no abrupt change in mechanical properties on heating. In contrast, copolymers including methyl acrylate polymeric blocks as the soft segments show shape memory properties even when dry.

30        Certain polymers, for example, poly(ethylene oxide-co-propylene oxide) block copolymers (PLURONICS™, BASF) are soluble in water at temperatures

lower than body temperature and become hydrogels at temperatures higher than body temperature. Incorporation of these polymers as blocks in shape memory polymers provides the shape memory polymers with the ability to response to changes in temperature in a manner totally opposite that of typical shape memory polymers. These materials recover their shape when cooled below their shape recovery temperature, rather than being heated above their shape recovery temperature. This effect is called inversed thermal shape memory effect. Shape memory polymer compositions including these polymer blocks are useful in various biomedical applications where the polymer can be inserted as a liquid, and cooled to recover an intended shape in situ. The inverse thermal shape memory effect can be obtained by incorporating two different blocks into a polymer that are miscible at temperatures lower than  $T_{misc}$  but are immiscible at higher temperatures. The phase separation at higher temperatures stabilizes the temporary shape.

Various polymers, such as polyacetylene and polypyrrole, are conducting polymers and such polymers can be used in conjunction with the devices of the present invention.

In a preferred embodiment, the shape memory polymer composition is able to hold more than one shape in memory. For example, the composition can include a hard segment and at least two soft segments, wherein the  $T_{trans}$  of the hard segment is between  $-30$  and  $270^{\circ}\text{C}$ , and is at least  $10^{\circ}\text{C}$ , and preferably  $20^{\circ}\text{C}$ , higher than the  $T_{trans}$  of one of the soft segments, and the  $T_{trans}$  of each subsequent soft segment is at least  $10^{\circ}\text{C}$ , and preferably  $20^{\circ}\text{C}$ , lower than the  $T_{trans}$  of the preceding soft segment. Optionally, one or more of the segments can be biodegradable or linked to another segment via a biodegradable linkage, such as ester-, amide-, anhydride-, carbonate-, or orthoester linkages.

The shape memory effect is based on the polymer morphology. With respect to thermoplastic elastomers, the original shape of an object is fixed by physical crosslinks caused by the hard segment. With respect to thermoset polymers, the soft segments are covalently crosslinked instead of having hard



segments. The original shape is set by the crosslinking process.

5 The polymers can be in the form of linear diblock-, triblock-, tetrablock, or multiblock copolymers, branch or graft polymers, thermoplastic elastomers, which contain dendritic structures, and blends thereof. The thermoplastic shape memory polymer composition also can be a blend of one or more homo- or co-polymer with one or more diblock-, triblock-, tetrablock, or multiblock copolymers, branch or graft polymers. These types of polymers are well known to those of skill in the art.

10 The polymers can be thermoset polymers. There are four different types of thermoset polymers that have shape memory capability. These include polymer networks, semi-interpenetrating networks, interpenetrating networks, and mixed-interpenetrating networks.

15 A polymer network is prepared by covalently crosslinking macromonomers, i.e., polymers that contain polymerizable end groups such as carbon-carbon double bonds. The polymerization process can be induced by using light or heat sensitive initiators or by curing with ultraviolet light ("UV-light") without an initiator. Shape memory polymer networks are prepared by crosslinking one or more soft segments which correspond to one or more thermal transitions.

20

In one embodiment, the crosslinking is performed using a photocrosslinker and requires no chemical initiator. The photocrosslinker advantageously eliminates the need for initiator molecules, which can be toxic.

25 Interpenetrating networks ("IPN") are defined as networks where two components are crosslinked, but not to each other. The original shape is determined by the network with the highest crosslink density and the highest mechanical strength. The material has at least two  $T_{trans}$  corresponding to the different soft segments of both networks.

30

A mixed IPN includes at least one physically crosslinked polymer network (a

thermoplastic polymer) and at least one covalently crosslinked polymer network (a thermoset polymer) that cannot be separated by any physical methods. The original shape is set by the covalently crosslinked network. The temporary shapes correspond to the  $T_{trans}$  of the soft segments and the  $T_{trans}$  of the hard segment of the thermoplastic elastomer component.

A particularly preferred mixed interpenetrating network is prepared by polymerizing a reactive macromonomer in the presence of a thermoplastic polymer, for example, by the photopolymerization of carbon-carbon double bonds. In this embodiment, the ratio by weight of thermoset polymer to thermoplastic polymer is preferably between 5:95 and 95:5, more preferably, between 20:80 and 80:20.

Semi-interpenetrating networks ("semi-IPN") are defined as two independent components, where one component is a crosslinked polymer (a polymer network) and the other component is a non-crosslinked polymer (a homopolymer or copolymer), wherein the components cannot be separated by physical methods. The semi-IPN has at least one thermal transition corresponding to the soft segment(s) and the homo- or co-polymer components. The crosslinked polymer preferably constitutes between about 10 and 90% by weight of the semi-interpenetrating network composition.

The shape memory polymers can exist as physical mixtures of thermoplastic polymers. In one embodiment, a shape memory polymer composition can be prepared by interacting or blending two thermoplastic polymers. The polymers can be semicrystalline homopolymers, semicrystalline copolymers, thermoplastic elastomers with linear chains, thermoplastic elastomers with side chains or any kind of dendritic structural elements, and branched copolymers, and these can be blended in any combination thereof.

For example, a multiblock copolymer with a hard segment with a relatively

high  $T_{\text{trans}}$  and a soft segment with a relatively low  $T_{\text{trans}}$  can be mixed or blended with a second multiblock copolymer with a hard segment with a relatively low  $T_{\text{trans}}$  and the same soft segment as that in the first multiblock copolymer. The soft segments in both multiblock copolymers are identical, so the polymers are miscible in each other when the soft segments are melted. There are three transition temperatures in the resulting blend -that of the first hard segment, that of the second hard segment, and that of the soft segment. Accordingly, these materials are able to memorize two different shapes. The mechanical properties of these polymers can be adjusted by the changing the weight ratio of the two polymers.

Other kinds of blends of at least two multiblock copolymers, in which at least one of the segments is miscible with at least one of the segments of the other multiblock copolymers, can be prepared. If two different segments are miscible and build one domain together, then the thermal transition of this domain depends on the weight content of the two segments. The maximum number of memorized shapes results from the number of thermal transitions of the blend.

Shape memory blends can have better shape memory capabilities than the blend components alone. Shape memory blends are composed of at least one multiblock copolymer and at least one homo- or copolymer. Di-, tri-, or tetra-block copolymers should be suitable substitutes for a multiblock copolymer.

In a preferred embodiment, the shape memory polymeric composition includes at least one hard segment and at least one soft segment or multiple soft segments that are covalently crosslinked, wherein at least two of the segments are linked via a functional group which is cleavable under application of light, changes in ionic concentration, changes in pH, electric field, magnetic field, and/or ultrasound. In addition to changing shape in response to changes in temperature, the composition can change its shape in response to application of light, changes in ionic concentration, changes in pH, electric field, magnetic field and/or ultrasound. The temporary shape in these polymers is fixed by the covalent crosslinks.

Various functional groups are known to crosslink in the presence of certain ions or in response to changes in pH. For example, calcium ions are known to crosslink amine and alcohol groups, i.e., the amine groups on alginate can be crosslinked with calcium ions. Also, carboxylate and amine groups become charged species at certain pHs. When these species are charged, they can crosslink with ions of the opposite charge. The presence of groups that respond to changes in the concentration of an ionic species and/or to changes in pH on hard and/or soft segments results in reversible linkages between these segments. One can fix the shape of an object while crosslinking the segments. After the shape has been deformed, alteration of the ionic concentration or pH can result in cleavage of the ionic interactions that formed the crosslinks between the segments, thereby relieving the strain caused by the deformation and thus returning the object to its original shape.

Various materials contain reactive functional groups that fragment in response to applied ultrasound. Examples of these groups are those that form stable radicals, such as nitroso and triphenylmethane groups. One can fix the shape of an object while forming bonds between two or more soft segments, for example by using heat or light. After the shape is deformed, the application of ultrasound can break the bonds between the soft segments, and relieve the strain caused by the deformation. The object will then return to its original shape.

The polymer used to form the segments in the SMPs described above are either commercially available or can be synthesized using routine chemistry. Those of skill in the art can readily prepare the polymers using known chemistry.

The compositions can be formed into a first shape under appropriate conditions, for example, at a temperature above the  $T_{trans}$  of the hard segments, and allowed to cool below the  $T_{trans}$  of the soft segment(s). Standard techniques are extrusion and injection molding. Optionally, the object can be re-formed into a second shape. Upon application of heat or other appropriate set of conditions, the

object returns to original shape.

Thermoset polymers can be prepared by extruding the pre-polymerized material (macromonomers), and fixing the original shape at a temperature above the  $T_{trans}$  of the thermoset polymer, for example, by photocuring reactive groups on the monomer. The temporary shape is fixed by cooling the material below  $T_{trans}$  after deforming the material.

The crosslinking also can be performed in a solution of the macromonomers. The solvent is removed from the formed gel in a subsequent step.

Those compositions formed of thermoplastic polymers can be blown, extruded into sheets or shaped by injection molding, for example, to form fibers. The compositions can also be shaped by other methods known to those of skill in the art for shaping solid objects, for example, laser ablation, micromachining, use of a hot wire, and by CAD/CAM (computer aided design/computer aided manufacture) processes. These processes are preferred for shaping thermoset polymers.

For several applications it is advantageous to go in small steps from a temporary shape to another temporary shape or the original shape. It is possible to go back and forth between shapes as needed, under the control of an operator.

Usually the  $T_{trans}$  of a shape memory polymer is sharp, so that the polymer can recover its original shape simply by heating the material only a few degrees Celsius. In an alternate embodiment, however, the shape memory polymer has a broad thermal transition, such that the original shape is fully recovered only when the polymer is heated higher than the upper limit of the thermal transition. A partial recovery occurs when heating at a temperature between the lower and the upper limits of the thermal transition. In this embodiment, the trigger is the temperature, and the effect is essentially independent of the time interval of heat application.

A certain amount of energy needs to be transferred to the shape memory polymer in order to recover a memorized shape. For the thermal shape memory effect, the amount of energy required to fully recover a memorized shape depends on the heat capacity of the material. In a preferred embodiment of a thermal shape memory effect, the polymer has a sharp thermal transition, which is triggered based on the duration the material is exposed to a temperature greater than  $T_{trans}$ . Other factors affecting the transition include the mass or size of the material, and the temperature and heat transfer coefficient of the medium or environment in contact with (and used to heat) the material. For example, the higher the temperature of the environment, the more quickly the memorized shape is recovered.

In case of the classical thermal shape memory effect, the entire polymer must be heated by application (and transfer) of heat energy from an external source in order to recover the original shape. In an alternate embodiment, the polymer is heated by energy sources other than temperature. Using these techniques it is possible not only to heat the whole shape memory device, but also selective parts of the shape memory device (another way of triggering and enhancing control to recover the original shape).

Polymers absorb light at different wavelengths, depending on their chemical structure. Polymers typically show strong absorption of radiation in the infrared (IR) and near-infrared (NIR) region. The strongest and most suitable absorption ranges for a particular polymer application can be identified using IR or NIR spectroscopy. Shape memory polymers also can show strong absorption in the ultraviolet (UV) region. The polymer can be cured with light including at least one of the specified frequencies in its spectra, such that the polymer will absorb the light energy and heat up.

The absorption characteristics of the shape memory polymer can be modified by the addition of a chromophore, which is a moiety, functional group, or molecule showing strong absorption in specific regions of the UV/visible/IR/NIR

microwave spectrum. The chromophor can be covalently bound to the polymer, combined as a physical mixture with the polymer, or both.

5 In a preferred biomedical embodiment, light can be used to non-invasively control an implanted SMP device. For example, the implanted polymer can be cured using specific external light sources that do not simultaneously heat tissue, serum, or other parts of the physiological environment surrounding the SMP implant. Such a light source (e.g., lamp) should emit one or more frequencies of light (e.g., near infrared, "NR") that are not absorbed by the physiological  
10 environment, but which are absorbed by the shape memory material. The use of NIR light is known in the diagnostics art.

15 In an alternate embodiment, the technique of interference is applied to control the light frequency applied to an implanted SMP. Interference provides three-dimensional (3-D) control of the region being cured, as the specific frequency of light being absorbed by the shape memory device is produced at a specified location by the interference of two or more beams crossed at the specified location.

The sources of the beams are outside the body, and the frequencies of the beams  
20 generally are modulated radio frequencies selected to produce the desired application frequency from the resulting interference.

25 In an alternate embodiment, gas bubbles or bubble containing liquids, preferably fluorocarbons, are incorporated in the shape memory device. Using standard ultrasound technology, one can induce a cavitation effect in the gas/liquid to heat the SMP. Techniques for 3-D controlled application of ultrasound are known in the art of biomedical diagnostics.

30 It is also possible to effect energy transfers based on the interaction of the shape memory polymer and electromagnetic fields. Use of electromagnetic fields to induce heating or localized temperature changes are well known. In yet another

embodiment, energy transfer is produced based on non-radiation effects, such as Foerster-Perrin energy transfer.

Shape memory polymer compositions can be prepared to have two original  
5 (permanent) shapes, i.e. a two-way shape memory effect. These systems always  
consist of at least two components. The components are combined by layer  
techniques (similarly to bimetals) or are interpenetrating networks. By changing the  
temperature, the shape memory device changes its shape in the direction of  
permanent shape 1 or permanent shape 2. Each of the permanent shapes belongs  
10 to one component of the device. The shapes of the device always are in  
equilibrium between both shapes. The temperature dependence of the shape is  
caused by the fact that the mechanical properties of one component ("component  
A") are almost independent from the temperature in the temperature interval of  
interest. The mechanical properties of the other component ("component B")  
15 depend on the temperature. In one embodiment, component B becomes stronger  
at low temperatures compared to component A, while component A is stronger at  
high temperatures and determines the actual shape. A two-way memory device  
can be prepared by (a) setting the original shape of component A; (b) deforming the  
device into original shape of component B; and (c) fixing an original shape of  
20 component B while applying a stress to the component.

The recovery of the original shape of a shape memory polymer can be  
initiated by a hydrolytic degradation process. In a preferred embodiment, this  
feature is incorporated into a system including a thermoplastic polymer composed  
25 of a hard segment and at least one soft segment or a thermoset containing at least  
one soft segment (single component systems). In these polymers, two soft  
segments can be linked by a readily hydrolyzable bond. The term "readily  
hydrolyzable bond" is used herein to refer to groups having a hydrolysis rate that is  
greater than that for other functional groups in the polymer. The original shape of  
30 these polymers is determined by the hard segments (thermoplastic material) or the  
covalent crosslinks (thermoset). The temporary shape is fixed by the crosslinks



between two soft segments after deforming the device. When the crosslinks between the soft segments are hydrolyzed, the original shape will be recovered. Readily hydrolyzable functional groups include activated ester bonds, such as glycolyl glycolate, and anhydride bonds.

5

In another preferred embodiment, the polymer is a two-component system, in which at least one component is a covalent network, such as an IPN, a mixed-IPN, or a semi-IPN. The covalent network is an amorphous network having a very low  $T_{trans}$ . The covalent network determines the original shape of the system, and  
10 the second component deforms the system to fix the temporary shape. The second component is another network in the case of an IPN, a homo- or co-polymer in the case of a semi-IPN, and a thermoplastic elastomer in the case of a mixed-IPN. The first component (covalent network) hydrolyzes more slowly than the second component, such that the polymer recovers its original shape when the  
15 second component is degraded.

Shape memory polymer compositions, articles of manufacture thereof, and methods of preparation and use thereof are described. In a preferred embodiment, the shape memory polymer composition can hold more than one shape in memory. For example, the composition can include a hard segment and at least two soft  
20 segments. The  $T_{trans}$  of the hard segment is at least 10°C, and preferably 20 °C, higher than the  $T_{trans}$  of one of the soft segments, and the  $T_{trans}$  of each subsequent soft segment is at least 10°C, and preferably 20°C, lower than the  $T_{trans}$  of the preceding soft segment. A multiblock copolymer with a hard segment with a relatively high  $T_{trans}$  and a soft segment with a relatively low  $T_{trans}$  can be mixed or  
25 blended with a second multiblock copolymer with a hard segment with a relatively low  $T_{trans}$  and the same soft segment as that in the first multiblock copolymer. Since the soft segments in both multiblock copolymers are identical, the polymers are miscible in each other when the soft segments are melted. The resulting blend has three transition temperatures: one for the first hard segment, one for the  
30 second hard segment, and one for the soft segment. Accordingly, these materials are able to memorize two different shapes.

Any polymers that are crystalline or amorphous and that have a  $T_{\text{trans}}$  within the range defined herein can be used to form the hard and soft segments. The melting point or glass transition temperature (hereinafter, the  $T_{\text{trans}}$ ) of the hard segment is at least 10°C, and preferably 20°C, higher than the  $T_{\text{trans}}$  of the soft segment. The  $T_{\text{trans}}$  of the hard segment is preferably between -30 and 270°C, and more preferably between 30 and 150°C. The ratio by weight of the hard segment:soft segments is between about 5:95 and 95:5, preferably between 20:80 and 80:20.

In some embodiments, the shape memory polymers contain at least one physical crosslink (physical interaction of the hard segment) or contain covalent crosslinks instead of a hard segment. The shape memory polymers also can be interpenetrating networks or semi-interpenetrating networks. In addition to changes in state from a solid to liquid state (melting point or glass transition temperature), hard and soft segments can undergo solid-to-solid state transitions, and can undergo ionic interactions involving polyelectrolyte segments or supramolecular effects based on highly organized hydrogen bonds.

Articles of manufacture can be prepared from the shape memory polymer compositions, for example, by injection molding, blowing, extrusion, and laser ablation. To prepare an object having a shape in memory, the object can be formed at a temperature above the  $T_{\text{trans}}$  of the hard segment, and cooled to a temperature below the  $T_{\text{trans}}$  of the soft segment. If the object subsequently is formed into a second shape, the object can be returned to its original shape by heating the object above the  $T_{\text{trans}}$  of the soft segment and below the  $T_{\text{trans}}$  of the hard segment.

Articles of manufacture with two or more shapes in memory can be prepared by forming a polymer composition with a hard segment, a first soft segment, and a second soft segment, where the first soft segment has a  $T_{\text{trans}}$  at least 10°C below

that of the hard segment and at least 10°C above that of the second soft segment. After the composition is shaped at a temperature above the  $T_{trans}$  of the hard segment, it can be cooled to a temperature below that of the  $T_{trans}$  of the first soft segment and above that of the second soft segment and formed into a second shape. The composition can be formed into a third shape after it has been cooled below the  $T_{trans}$  of the second soft segment. The composition can be heated above the  $T_{trans}$  of the second soft segment to return the composition to the second shape. The composition can be heated above the  $T_{trans}$  of the first soft segment to return the composition to the first shape. The composition can also be heated above the  $T_{trans}$  of the hard segment, at which point the composition loses the memory of the first and second shapes and can be reshaped using the method described above.

Thermoset polymers can be prepared by pre-shaping macromonomers, for example, by extrusion, and fixing the original shape at a temperature above the  $T_{trans}$  of the thermoset polymer, for example, by photocuring reactive groups on the macromonomer. The original shape, however, can only be programmed one time.

In a preferred embodiment, the shape change occurs in response to a change in temperature. In another embodiment, however, the composition can change its shape in response to application of light, changes in ionic concentration and/or pH, electric field, magnetic field or ultrasound. For example, a SMP can include at least one hard segment and at least one soft segment, wherein at least two of the segments, preferably two soft segments, are linked to each other via a functional group that is cleavable under application of light, electric field, magnetic field or ultrasound. The temporary shape is fixed by crosslinking the linear polymers. By cleaving those links the original shape can be recovered. The stimuli for crosslinking and cleaving these bonds can be the same or different.

Deployment of bioresorbable electrodes with or without shape memory polymer with different deployment characteristics (force and rate) can be achieved through: choice of polymer, the addition of a second phase (co-polymer or polymer blend), degree of cross-linking and via the incorporation of a second phase of

nanoparticulates or nanofibers. Smp electrodes can deploy nanoparticulates, nanofibers, microwires, and nanowires with improved electrical properties. Microwires and nanowires can be coated with alumina using atomic layer deposition in order to insulate the surface of the electrode, except at the tip. The coating of the present invention enables the use of ductile metal microwires and nanowires that would buckle when inserted alone. Further, the use of bioresorbable polymers with or without shape memory effects can be used to deploy microwire and nanowires electrodes in tissue leaving the wire suspended following resorption. This slow deployment (minutes to days) of electrodes of other materials can be used to minimize tissue reactivity leading to improved long term performance. The reactivity is lessened in that the smps are slowly resorbed into the tissue and thus gradually expose the electrodes to the tissue. The gradual exposure lessens the immune response to the electrodes.

The surface morphology of the coating can be modified in the nano and micro scale to modify the interaction of the electrodes with surrounding tissue. The surface can be modified using techniques known to those of skill in the art. Examples of such techniques include, but are not limited to, chemically scuffing or altering the surface, mechanical scuffing of the surface, and nanotexturing the surface.

Biologicals or chemicals can be incorporated into the bioresorbable electrodes that can be released upon resorption to modify tissue reactivity, promote or inhibit cell and extracellular matrix adhesion or to serve as a biological tracer of insertion site. Timing of release can be tailored by changing the properties of the bioresorbable polymer. Biologicals or chemicals can be incorporated on the surface of shape memory polymer electrodes that can be released or directly interact with surrounding tissue to modify tissue reactivity and promote or inhibit cell and extracellular matrix adhesion. Examples of such material include, but are not limited to, immunosuppressive compounds and agents. Immunosuppressive agents are defined as agents that suppress immune responses. The agents can

include, but are not limited to, immunoprotected cells, such as Sertoli cells, stem cells, stem cell by-products, or other compounds that create an immunosuppressive effect. Examples of such immunosuppressive compounds include, but are not limited to, PKC inhibitors, glutamate inhibitors, cyclosporins, FK506, corticosteroids, and ascomycins. A glutamate inhibitor is defined as any of a class of pharmacological agents which prevent the binding and/or action of glutamate (or glutamatergic agonists) at ionotropic glutamate receptors, resulting in reduced or completely blocked ion-conductance of such receptors. Examples of appropriate glutamate inhibitors include, but are not limited to, carbidopa, levodopa, and sodium-channel blockers.

Additionally, the coating can be used in conjunction with a bioresorbable scaffolding. The scaffolding enables the nanowires to be inserted without affecting the surrounding tissue. Then, as the scaffolding is resorbed into the tissue, the nanowires are slowly exposed to the tissue, thus lessening the immune response to the nanowires.

The invention is further described in detail by reference to the following experimental examples. These examples are provided for the purpose of illustration only, and are not intended to be limiting unless otherwise specified. Thus, the invention should in no way be construed as being limited to the following examples, but rather, should be construed to encompass any and all variations which become evident as a result of the teaching provided herein.

## **EXAMPLES**

### **Example 1:**

The olfactory system in mice was used to test CEMS-based brain implants with integrated electronics for biocompatibility, reliability and signal to noise characteristics. Implants developed were used to study the neural basis for

olfactory behavior.

Insertion of electrodes in brain tissue evokes an inflammatory astrocytic scar reaction that severely limits long-term electrode performance. The rate of electrode  
5 insertion and the composition of electrode coatings are major factors contributing to the astrocytic scar. The use of low modulus, compliant materials capable of slow deployment *in situ* minimizes adverse long-term tissue reactivity to electrode implantation. In order to deploy electrodes *in situ* at slow rates (hours to days), thermally actuated composite electrodes fabricated from shape memory polymers  
10 (smmps) were used. Smmps were designed to deploy at body temperature at different rates, thereby enabling a thorough study of the effect of rate of deployment on the extent of astrocytic scar reaction. Composite smp electrodes incorporated compliant gold conductors and were attached to a base of lightweight polyimide. Different coatings of the tip of the electrode were tested for biocompatibility,  
15 including bioresorbable coatings. The extent of the astrocytic scar reaction, necrosis, microglial infiltration and apoptosis were determined by immunohistochemistry. Long-term electrode reliability was quantified by recording single unit responses at different times post-implantation. Changes in electrical parameters were correlated to changes in the astrocytic scar reaction.

20 Electronics were designed to perform the key functions of electrode site multiplexing, low-noise signal amplification, analog-to-digital conversion and digital data transmission. The designs emphasize the critical requirements for optimal signal-to-noise performance, ultra low-power operation and circuit area  
25 minimization necessary for incorporation into the CEMS implant. Impedance characteristics of electrodes were measured as well as responsiveness of electrodes to artificial spike-shaped voltage changes *in vitro*, and were compared to long-term changes in electrical properties due to encapsulation by astrocytes and chemical changes of the surface of the conductor *in vivo*. In addition, long-term  
30 changes in impedance of implanted electrodes *in vivo* were measured. The

electronics were optimized to measure extracellular spike signals given constraints imposed by electrode characteristics, materials engineering and biocompatibility.

5 The electronic implant and the smp electrode assembly were linked to a surface module attached to the cranium that serves the purpose of downloading data stored in the implant. The CEMS implant, encapsulated in polyimide, was inserted on the dorsal surface of the mouse olfactory bulb and was tested for long-term performance 1 day to 12 weeks postimplantation. Performance was assessed through long-term signal-to noise measurements of single units. The CEMS  
10 implant was also tested for biocompatibility by assessing the extent of tissue reactivity using immunohistochemistry.

Example 2:

15 **Shape memory polymers.**

Shape memory polymers (smp's) and smp composites (Gall et al., 2002; Tobushi et al., 1992) are an attractive compliant material that has not been proposed for use in electrodes. The thermo-mechanical response of shape  
20 memory polymers is shown schematically in Figure 1, as defined by four critical temperatures. The glass transition temperature,  $T_g$ , is the reference point for thermo-mechanical deformation and recovery. An advantage of smp's is that  $T_g$  can be easily varied over a temperature range of several hundred degrees by control of chemistry or degree of cross-linking. The deformation temperature,  $T_d$ , is  
25 the temperature at which the polymer is deformed into its temporary shape (Figure 1). The initial deformation at  $T_d$  can occur above or well below  $T_g$  depending on the desired recovery response (Gall et al., 2002). The storage temperature,  $T_s$ , is below  $T_d$  and constitutes the temperature at which the temporary shape is stable over time. After deformation at  $T_d$ , the material is typically cooled to  $T_s$  with varying  
30 degrees of strain/stress constraint ranging from no constraint to full constraint (Figure 1). The recovery temperature,  $T_r$ , represents the temperature range at

which the material recovers its original shape during heating. Recovery can be accomplished isothermally by heating to a fixed  $T_r$  and then holding, or by continued heating up to and past  $T_r$  (Gall et al., 2002;Liu et al., 2003).

5           Because these polymers can be fabricated to the micron scale using photolithographic techniques this allows for reproducible fabrication of compliant electrodes. Further, by adding different materials it is possible to control the actuation force and rate of deployment (minutes to hours), making it possible to  
10       conductive, smp's can be fabricated with microwire inclusions or can have evaporated conductive wires patterned on the surface using electron beam evaporated gold.

          One of the major limitations of present technology in implantable electrodes  
15       is poor long-term biocompatibility and degradation of electrical reliability. Ideally, an implanted electrode should not impact the surrounding cells thereby providing for stable long-term recording of extracellular field potentials from neighboring neurons. Electrode materials should be compliant thereby minimizing differential movement of the electrode with respect to brain tissue. However, immediately upon insertion  
20       of microwire or silicon micromachined electrodes, there is tissue inflammation and necrotic cell death. Interestingly, the quality of recording from chronic microwire electrodes *increases* in the first few days of recording, likely due to decrease in tissue inflammation and edema. However, a longer-term reactive astrocytic reaction ensues that result in physical blockage of the electrode by a surrounding  
25       sheath of reactive astrocytes. The "astrocytic scar" as well as corrosion of the electrode surface contribute to progressive signal degradation (Maynard et al., 2000;Nadol, Jr. et al., 2001;Rousche et al., 2001;Rousche and Normann, 1998;Turner et al., 1999;Williams et al., 1999). Two components of the astrocytic tissue reaction, short-term and long term, have been described. It has been  
30       postulated that electrode geometry and device size influence only the short term reaction. The implication being that the long term reactions are exclusively due to



material biocompatibility (Szarowski et al., 2003). While this conclusion is likely correct for the conditions tested in the Szarowski manuscript, the range of electrode cross-sections tested was limited, and bioresorbable materials were not used in that study. In addition, a causal relationship between the long-term and short-term reactions cannot be discarded in that study because the short-term reaction was significant under all conditions tested in that study.

The causal relationship between the initial necrosis and subsequent inflammation and astrocytic scar is not well understood for electrode insertion. Brain stab wound, a process with significant parallels to electrode insertion injury, is much better understood. Studies of brain stab injury indicate that the insertion of a sharp foreign object into brain tissue elicits blood spillage and cell necrosis thereby causing large increases in the concentration of glutamate, a molecule that is normally used by the central nervous system as a neurotransmitter, but becomes excitotoxic at high concentration. Glutamate causes excitotoxicity in neurons promoting further necrosis and triggering an inflammatory reaction with recruitment of microglia, the immune cells of the nervous system. Within a few days signaling molecules released by the microglia, presumably cytokines, elicit formation of an "astrocytic scar" formed of reactive astrocytes surrounding the wound. In parallel, and perhaps mediated through microglia activation, there is a slower development of apoptosis (programmed cell death) in a period of days to weeks (Beattie et al., 2000; Citron et al., 2000; Eldadah and Faden, 2000; Giulian et al., 1989; Knobloch et al., 2002; Krum et al., 2002; Roitbak and Sykova, 1999; Snider et al., 1999; Turner et al., 1999; Tzeng and Wu, 1999).

Several aspects of tissue response to stab wound are problematic for long-term measurement with microelectrode arrays. Astrocytic scars are an electrical barrier between the electrodes and the neighboring neurons, resulting in decreased signal-to-noise ratio. In addition, given that there is little adult neurogenesis, neuronal apoptosis causes irreversible loss of the source of electrical signals. It is therefore extremely important to decrease the magnitude of the inflammatory

reaction to electrode insertion. A major hypothesis in stab brain injury is that the adverse reaction to the stab is triggered by large increases in glutamate concentration that cannot be handled by normal glutamate homeostasis mechanisms. Since a major source of glutamate is spillage from injured cells and damaged blood vessels in the electrode insertion path, slow rates of insertion (hours to days) results in a smaller increase in glutamate concentration and in a diminished tissue reaction. This in turn leads to improved long term performance of electrodes.

#### **Bioresorbable polymers.**

Polyesters based on polylactic acid (PLA), polyglycolic acid (PGA) and their copolymers are the most commonly used materials for their bioresorbable characteristics. They are biocompatible and FDA approved (for a particular form of synthesis) (Vert et al., 1998). While the mechanisms of hydrolytic degradation are complex, the rate of degradation ranging from weeks to months can be controlled either through composition as in forming polymer blends or through the addition of initiators. The breakdown products of PLA and PGA are L- or D- lactic and glycolic acid respectively (Ignatius and Claes, 1996), all of which are normally present in the human body. These are typically metabolized by cells surrounding the material by means of the citrate cycle yielding carbon dioxide which is finally eliminated by respiration (Brandt et al., 1984). The combination of bioresorbability and shape memory effect has been studied by (Lendlein and Langer, 2002) based on a linear, phase-segregated multiblock copolymer as the structural concept with successful results in terms of cyclic thermomechanical properties showing deployment at 37°C and with linear mass loss of around 50% in 300 days.

Typically, electrodes are inserted quickly into tissue (in the order of minutes). Indeed, several individuals have proposed that inserting electrodes quickly by shooting them with a pneumatic gun can be advantageous. If slow deployment were performed by using a micromanipulator, patients would have to be kept under

anesthesia for long periods of time thereby increasing the risk of death. The use of shape memory polymers to slowly deploy electrodes eliminates the need to maintain the individuals under anesthesia while enabling a slow deployment.

5 Embedded smp electrodes can be sectioned for histological processing in olfactory bulb *in situ*. Complete analysis of the tissue response to electrode insertion ideally includes the histological examination of the brain with the electrode *in situ*. Most studies remove the implant prior to sectioning of the tissue. Alternatively, some investigators perform the laborious task of attempting to section  
10 parallel to implants in order not to disrupt the tissue when the sectioning knife contacts the implant material. The present invention instead enables fine wires (<25  $\mu\text{m}$ ) to be sectioned or embedded without disrupting the tissue.

Individual wires (25  $\mu\text{m}$  diameter) or embedded smp electrodes were  
15 inserted into the olfactory bulbs of mice immediately after euthanasia. The bulbs were then removed, immersion fixed and prepared for cryosectioning (18  $\mu\text{m}$  sections). It was not possible to section any of the wires tested (stainless steel, W, W/Ir, Au, Ag, Ni) without some damage to the tissue. However, the softer metals (e.g. Au and Ag, Figure 2(a)) sectioned, albeit with some tearing. Gold and silver  
20 wires that were embedded in smp were routinely cut without causing tissue disruption (Figure 2(b)). Generally, the smp remained attached to the tissue section after processing. The ability for the embedded smp's to remain adhered to the tissue during processing increases the ability to properly analyze the tissue response due to implantation of novel electrode materials.

#### 25 Initial characterization of biocompatibility of smp electrodes.

Figure 3 shows a cross section of an olfactory bulb one week after  
implantation with an smp beam. The section was reacted with an antibody to  
30 GFAP, a selective marker of astrocytes, and counter stained with hemotaxolin and eosin. The implant caused gross disruption of tissue histology including a massive

infiltration of astrocytes around it. Additionally, slight increases in the number of microglia and apoptotic cells were detected. The extent of astrocytic scarring appears less than that reported for Si micromachined electrodes (Szarowski et al., 2003). Further, examination of an olfactory bulb two weeks after implantation (Figure 4) shows less astrocytosis compared to one week post-implantation (Figure 3). A decrease in astrocytosis with time was not evident in studies with Si micromachined electrodes (Szarowski et al., 2003), and indicates better biocompatibility for smp implant materials.

In order to explore the possibility that slow rates of implant insertion might cause decreased tissue reactivity, the astrocytic scarring resulting one week after insertion of a rapidly inserted smp beam (~1 mm/sec, Figure 3) was compared to an embedded gold microwire smp electrode inserted more slowly (1 mm/40 min, Figure 5) using an electronically controlled micromanipulator. The slowly deployed embedded smp electrode caused very little astrocytic scarring. This establishes that slow insertion of implants reduces the extent of damage to the tissue. Thermally-actuated smp electrodes that deploy over the course of many hours or days actually induces even less tissue damage.

Figure 6(a) shows the tip of an smp electrode without an embedded microwire partially inserted into a mouse olfactory bulb. Force of insertion was measured at NIST on the basis of Hooke's law using a piezoelectric actuator specifically designed to measure force in the 5  $\mu$ N-100 mN range. The smp materials were capable of providing sufficient stiffness to avoid kinking or buckling of the electrode as they were inserted into the mouse olfactory bulb even without the presence of the microwire for added rigidity. Figure 6(b) shows the force of insertion as a function of distance. The magnitude of the insertion forces measured in mouse olfactory bulb (ca 40  $\mu$ N) are consistent (after scaling for probe size) with forces measured in pig brain (ca 100 mN)(Miller et al., 2000). Forces measured in olfactory bulb are several orders of magnitude below the mN forces that can be

generated by smp materials. (Gall et al., 2002). Smp materials are capable of generating enough force for deployment in the brain following surgical implantation.

5        Figure 7 shows two designs for linear actuators, one with an embedded 25  $\mu\text{m}$  gold conductor. In the initial tests linear deployments of 280  $\mu\text{m}$  (Figure 7(b)) and 170  $\mu\text{m}$  (Figure 7(d)) were obtained. Deployment of 500  $\mu\text{m}$  is also obtainable.

#### **Shape memory effect of bioresorbable PGA polymers.**

10        An initial attempt has been made to evaluate the shape memory effect of bioresorbable PGA. Heating the polymer from the solid state and applying a compressive force at 120°C prior to cooling to room temperature shows the polymer retains the deformed pattern. Although the shape memory effect is weaker than that exhibited by epoxy based materials, initial measurements show that re-heating  
15        the PGA polymer results in recovery (Figure 8). These results are extremely encouraging since increasing the  $T_g$  by way of adding a second phase (e.g. blending with Poly Lactic Acid (PLA)) or cross-linking of the PGA polymer has a significant impact on the force of recovery.

20        Figure 1 is a schematic of the shape memory effect in polymers as defined by four critical temperatures. The value of  $T_g$  is a material property that can be altered depending on the application. Typically,  $T_s$  is always less than  $T_g$ , while  $T_d$  can be above or below  $T_g$ , depending on the desired recovery response. The value of  $T_r$  depends on both  $T_d$  and  $T_g$ ;

25        Figure 2 shows sections of olfactory bulb with (Figure 2a) 25  $\mu\text{m}$  gold microwire or (Figure 2b) embedded smp/gold electrode (150 X 300  $\mu\text{m}$ ). Implant in (Figure 2b) appears somewhat larger than the actual dimensions due to the angle of sectioning, the scale bar is 300  $\mu\text{m}$  and arrows point to gold microwire.

30        Figure 3 shows the tissue response to implantation of 100 X 200  $\mu\text{m}$  smp one week post-implantation. Implanted olfactory bulb (Figure 3a) showed a large

infiltration of astrocytes stained for GFAP (brown) around the implant compared to the contralateral bulb (Figure 3b), the scale bar is 200  $\mu$ m.

Figure 4 shows the tissue response to implantation of 100 X 200  $\mu$ m smp after two weeks. The astrocytic scar around the implant in (Figure 4a) is smaller and less dense than that for a one week implant (Figure 3). Note that the shape and size of the implant are odd due to the severe misalignment of the bulb before sectioning. Figure 4b shows the section through the control contralateral bulb, the scale bar is 200  $\mu$ m:

Figure 5 shows the tissue response to a one week "slowly" (1 mm/ 40 minutes) inserted smp/gold wire implant (75 X 200  $\mu$ m). The implanted bulb (Figure 5a) showed an increase in astrocytes around the implant when compared to the control bulb (Figure 5b), but the extent of the astrocytic scar was less than that seen for rapidly inserted implants (Figures 3,4). Notice that the presence of astrocytes in midline is a normal feature of the bulb.

Figure 6 shows the force measurement, wherein the top digital micrograph of an smp beam partially inserted into the olfactory bulb (on left) and the bottom is a force-displacement graph. Taper was entirely covered at 400  $\mu$ m, where the slope relates to the friction of insertion reaching a maximum of 0.1 mN.

Figure 7 shows two different designs (Figures 7a and b, and Figures 7c and d) for smp linear actuators with 25  $\mu$ m embedded gold wire in the compressed state (Figures 7 (a) and (c)) and following thermal actuation (Figures 7 (b) and (d)), the bars are 1 mm.

Figure 8 shows the shape memory effect in poly glycolic acid (PGA), (Figure 8a) the shape after deformation at 120°C, and (Figure 8b) subsequent recovery above  $T_g$ , the bar is 1 mm.

Throughout this application, various publications, including United States patents, are referenced by author and year and patents by number. Full citations for the publications are listed below. The disclosures of these publications and patents in their entireties are hereby incorporated by reference into this application  
5 in order to more fully describe the state of the art to which this invention pertains.

The invention has been described in an illustrative manner, and it is to be understood that the terminology that has been used is intended to be in the nature of words of description rather than of limitation.

10

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is, therefore, to be understood that within the scope of the appended claims, the invention can be practiced otherwise than as specifically described.

15

## **CLAIMS**

What is claimed is:

5           1.     An implantable electrode comprising a shape-memory polymer coated electrode.

          2.     The electrode according to claim 1, wherein said polymer is bioresorbable.

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          3.     The electrode according to claim 1, wherein said electrode further includes an anti-glutamate coating on an exterior surface of said electrode.

15

          4.     The electrode according to claim 1, wherein said electrode further includes an immunosuppressant coating on an exterior surface of said electrode.

          5.     A coating for an electrode, said coating comprising a shape-memory polymer.

20

          6.     The coating according to claim 5, wherein said polymer is bioresorbable.

          7.     The coating according to claim 5, wherein said coating further includes an anti-glutamate coating on an exterior surface of said electrode.

25

          8.     The coating according to claim 5, wherein said coating further includes an immunosuppressant coating on an exterior surface of the electrode.

30

          9.     A method for inserting an electrode into brain tissue by inserting the electrode of claim 1 into brain tissue.



10. The method according to claim 9, wherein said inserting step includes inserting the electrode into brain tissue and slowly resorbing the coating into the brain.

5

**SHAPE MEMORY POLYMER COATED ELECTRODES**

**ABSTRACT OF THE DISCLOSURE**

5        There is provided an implantable electrode having a shape-memory polymer coated electrode. A coating for an electrode, the coating includes a shape-memory polymer. A method for inserting an electrode into brain tissue by inserting an implantable electrode having a shape-memory polymer coated electrode into brain tissue.

10

Fig. 1. Schematic of the shape memory effect in polymers as defined by four critical temperatures. The value of  $T_g$  is a material property that can be altered depending on the application. Typically,  $T_g$  is always less than  $T_d$ , while  $T_r$  may be above or below  $T_d$ , depending on the desired recovery response. The value of  $T_s$  will depend on both  $T_d$  and  $T_r$ .

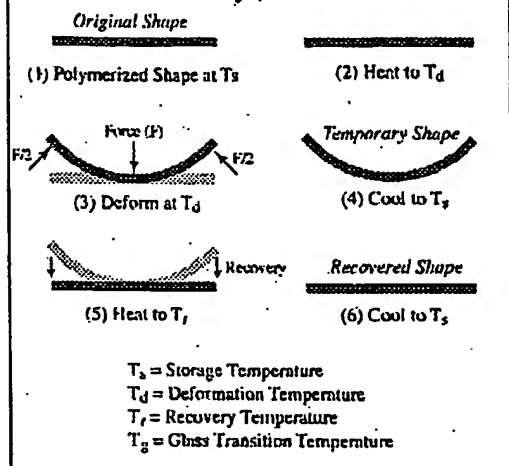
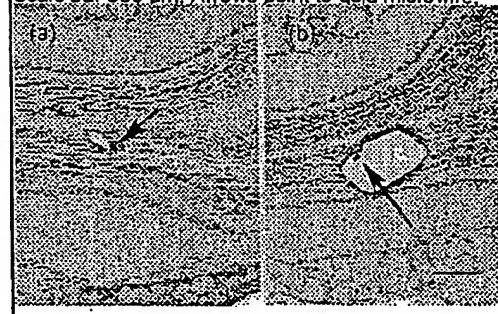
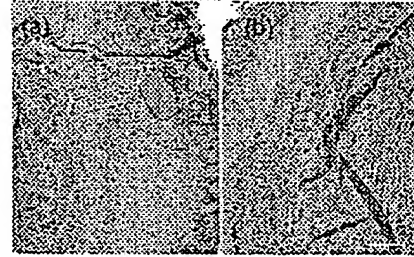


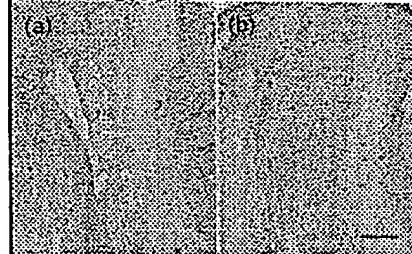
Fig. 2. Sections of olfactory bulb with (a) 25  $\mu$ m gold microwire or (b) embedded smp/gold electrode (150 X 300  $\mu$ m). Implant in (b) appears somewhat larger than the actual dimensions due to the angle of sectioning. Scale bar 300  $\mu$ m. Arrows point to gold microwire.



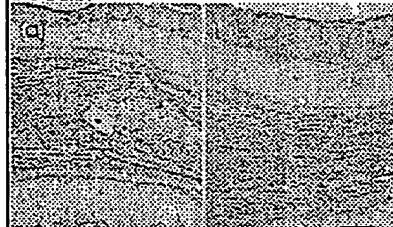
**Fig. 3.** Tissue response to implantation of 100 X 200  $\mu$ m smp one week post-implantation. Implanted olfactory bulb (a) showed a large infiltration of astrocytes stained for GFAP (brown) around the implant compared to the contralateral bulb (b). Scale bar=200  $\mu$ m.



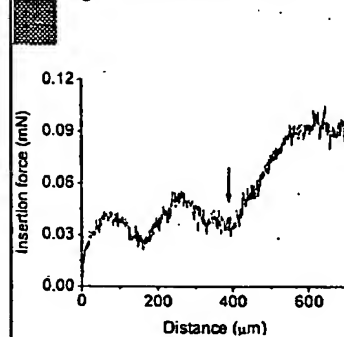
**Fig. 4.** Tissue response to implantation of 100 X 200  $\mu$ m smp after two weeks. The astrocytic scar around the implant in (a) is smaller and less dense than that for a one week implant (Fig. 3). Note that the shape and size of the implant are odd due to the severe misalignment of the bulb before sectioning. (b) Section through the control contralateral bulb. Scale bar=200  $\mu$ m.



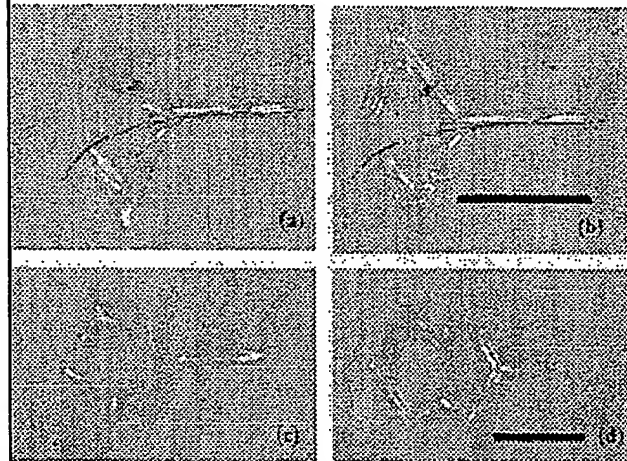
**Fig. 5.** Tissue response to a one week "slowly" (1 mm/ 40 minutes) inserted smp/gold wire implant (75 X 200  $\mu$ m). The implanted bulb (a) showed an increase in astrocytes around the implant when compared to the control bulb (b), but the extent of the astrocytic scar was less than that seen for rapidly inserted implants (Figs.4,5). Notice that the presence of astrocytes in midline is a normal feature of the bulb.



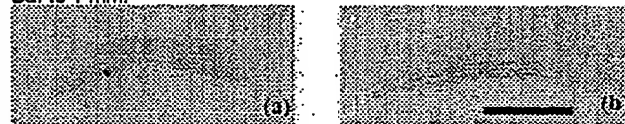
**Fig. 6. Force measurement.** Top Digital micrograph of an smp beam partially inserted into the olfactory bulb (on left). Bottom: Force-displacement graph. Taper was entirely covered at 400  $\mu\text{m}$ , where the slope relates to the friction of insertion reaching a maximum of 0.1 mN.



**Fig. 7. Two different designs (a and b, and c and d) for smp linear actuators with 25  $\mu\text{m}$  embedded gold wire in the compressed state ((a) and (c)) and following thermal actuation ((b) and (d)).** Bars are 1 mm.



**Fig. 8. Shape memory effect in poly glycolic acid (PGA).** (a) Shape after deformation at 120°C and (b) subsequent recovery above  $T_g$ . Bar is 1 mm.



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